SOIL MECHANICS FOR UNSATURATED SOILS

D. G. Fredlund
H. Rahardjo

Soil Mechanics for Unsaturated Soils

D. G. Fredlund, Ph.D.

Professor of Civil Engineering
University of Saskatchewan
Saskatoon, Saskatchewan

H. Rahardjo, Ph.D.

Senior Lecturer
School of Civil and Structural Engineering
Nanyang Technological University

A Wiley-Interscience Publication
JOHN WILEY & SONS, INC.
New York • Chichester • Brisbane • Toronto • Singapore

This text is printed on acid-free paper.

Library of Congress Cataloging in Publication Data:

Fredlund, D. G. (Delwyn G.), 1940–
Soil mechanics for unsaturated soils / D. G. Fredlund and H. Rahardjo
p. cm.
Includes bibliographical references and index.
ISBN 0-471-85008-X
1. Soil mechanics. 2. Soil moisture. 3. Soil—Testing.
I. Rahardjo, H. (Harianto) II. Title.
TA710.5.F73 1993
624.1'5136—dc20 92-30869

Printed in the United States of America

10 9 8 7 6 5 4 3 2

Dedicated

to our parents

George and Esther Fredlund

and

Sugiarto and Pauline Rahardjo

who taught us that the fear of the Lord was the beginning of wisdom and that the love of the Lord makes life worth living

Delwyn G. Fredlund
Harianto Rahardjo

FOREWORD

The appearance of a new book on Geotechnical Engineering is always an important occasion; but the appearance of the first book on an important aspect of Soil Mechanics is especially noteworthy. In this volume, Professor Fredlund and Dr. Rahardjo present the first textbook solely concerned with the behavior of unsaturated soils. The timing is particularly propitious.

It is evident that since much of the developed world enjoys a temperate climate, resulting in primarily saturated soil conditions, the literature has been biased toward problems involving saturated soils. Moreover, the theoretical understandings and associated experimental procedures required for an understanding of unsaturated soil behavior are intrinsically more complex than those required for saturated soil behavior. As a result, the ability to synthesize unsaturated soil mechanics has lagged behind its saturated counterpart. This has been to the detriment of both students and practitioners alike.

The climatic conditions that give rise to unsaturated soils can be found on every continent. Indeed, in some countries, unsaturated soil conditions dominate. The engineering problems associated with unsaturated soil mechanics extend over an enormous range. The requirements for design and construction of low-cost lightly loaded housing on expansive soils have been with us for a long time. More financial losses arise annually from damages due to unsaturated expansive soil behavior than from any other ground failure hazard. At the other extreme, unsaturated soils are used as a buffer material in almost every proposal for the underground storage of nuclear waste. Hence, the need to understand the mechanics of unsaturated soil behavior extends from concerns for low cost housing to some of the most complex environmental issues of our time.

I expect that this volume will quickly become the classic reference in its field. It will not be possible to teach, conduct research, or undertake modern design related to unsaturated soils without reference to Fredlund and Rahardjo. The authors have wisely maintained the framework of classical soil mechanics and sought to extend it in order to incorporate soil suction phenomena as an independent variable that is amenable to measurement and calculation. This will greatly facilitate the use of this comprehensive volume and quickly result in a more profound understanding of unsaturated soil behavior.

The road to this volume has been a difficult one. Many early leaders of Soil Mechanics pointed in the right direction, but it has taken more than thirty years of sustained effort to reach the end of the journey marked by this publication. All those who participated in the voyage should share pleasure in the outcome.

N. R. MORGENSTERN
University Professor of Civil Engineering

University of Alberta
April 1993

PREFACE

Numerous textbooks have been written on the subject of soil mechanics. The subject matter covered and the order of presentation vary somewhat from text to text, but the main emphasis is always on the application of the principles of soil mechanics to problems involving *saturated* soils.

A significant portion of the earth's surface is subjected to arid and semi-arid climatic conditions, and as a result, many of the soils encountered in engineering practice are unsaturated. This textbook addresses the subject of soil mechanics as it relates to the behavior of *unsaturated* soils. More specifically, the text addresses that class of problems where the soils have a matric suction or where the pore–water pressure is negative.

Whether the soil is unsaturated or saturated, it is the negative pore–water pressure that gives rise to this unique class of soil mechanics problems. When the pore–water pressure is negative, it is advantageous, and generally necessary, to use two independent stress state variables to describe the behavior of the soil. This is in constrast to saturated soil mechanics problems where it is possible to relate the behavior of the soil to one stress state variable, namely, the effective stress variable.

The terms *saturated soil mechanics* and *unsaturated soil mechanics* are primarily used to designate conditions where the pore–water pressures are positive and negative, respectively. Soils situated above the groundwater table have negative pore–water pressures. The engineering problems involved may range from the expansion of a swelling clay to the loss of shear strength in a slope. Microclimatic conditions in an area produce a surface flux boundary condition which produces flow through the upper portion of the soil profile.

It would appear that most problems addressed in *saturated* soil mechanics have a counter problem of interest in *unsaturated* soils. In addition, the remolding and compacting of soils is an important part of many engineering projects. Compacted soils have negative pore–water pressures. The range of subjects of interest involving negative pore–water pressures are vast, and the problems are becoming of increasing relevance, particularly in arid regions.

An attempt has been made to write this textbook in an introductory manner. However, the subject matter is inherently complex. The need for such a book is clearly demonstrated by engineering needs associated with various projects around the world. The frustrations are expressed primarily by engineers who have received advanced training in conventional soil mechanics, only to discover difficult problems in practice involving unsaturated soils for which their knowledge is limited.

The textbook makes no attempt to redevelop concepts well known to saturated soil mechanics. Rather, the book is designed to be an extension of classical saturated soil mechanics. As far as is possible, the principles and concepts for unsaturated soils are developed as extensions of the principles and concepts for saturated soils. In this way, the reader should be able to readily grasp the formulations required for unsaturated soil mechanics.

The general format for the textbook is similar to that used in most classical soil mechanics textbooks. The book starts by introducing the breadth of unsaturated soil mechanics problems. It then presents material related to the: 1) volume–mass properties, 2) stress state variables, 3) flow behavior, and 4) pore pressure parameters for unsaturated soils. The book then goes on to present material on the: 5) shear strength and 6) volume change behavior of unsaturated soils. The latter part of the book concludes with material on the transient processes of interest to geotechnical engineering.

A brief summary of the chapters of the textbook is as follows. Chapter 1 presents a brief history of developments related to the behavior of unsaturated soils. The need for an understanding of unsaturated soil mechanics is presented, along with the scope and description of common geotechnical problems. The nature of an unsaturated soil element is described, concentrating on the difference between a saturated and an unsaturated soil. Chapter 2 presents the phase properties and the volume–mass relations of interest to unsaturated soils. This chapter provides some overlap with classical soil mechanics, but emphasizes extensions to the theory. The steps involved in all derivations are described in detail in order to assist the reader in this relatively new field.

Chapter 3 is devoted to describing the stress state variables of relevance in solving engineering problems associated with soils having negative pore–water pressures. The concept of the stress state is presented in detail because of its extreme importance in understanding the formulations presented later in the textbook. One needs only to examine the importance of the role of the effective stress concept in the development of saturated soil mechanics to realize the importance of an acceptable description of the stress state for unsaturated soils. The authors believe that a thorough understanding of the stress state provides the basis for developing a transferable science for unsaturated soil mechanics.

A knowledge of the stress state reveals that the measurement of the pore–water pressure is mandatory. The measurement of highly negative pore–water pressures and soil suction is difficult. Chapter 4 summarizes techniques and devices that have been developed and used to measure negative pore–water pressures and soil suction.

There are three fundamental soil properties that are commonly associated with soil mechanics problems. The properties are: 1) coefficient of permeability, 2) shear strength parameters, and 3) volume change coefficients. These properties are covered in the next nine chapters. Each of the properties is addressed from three standpoints. First, the theory related to the soil property is presented. Second, the measurement of pertinent soil properties is discussed, along with the presentation of typical values. Third, the application of the soil properties to specific soil mechanics problems is formulated and discussed. The logistics of these chapters is as follows:

Chapters Presenting the Following Material

Soil Property	Theory	Measurement	Application
Permeability	5	6	7
Shear Strength	9	10	11
Volume Change	12	13	14

Descriptions of the equipment required for the measurement of the soil properties are presented under each of the "Measurement" chapters. The main application problems presented pertaining to permeability are two-dimensional, earth dam seepage analyses. For shear strength, the applications are lateral earth pressure, bearing capacity, and slope stability problems, with most emphasis on the latter. The primary volume change problem is the prediction of the heave of light structures.

Chapter 8 presents the theory and typical test results associated with pore pressure parameters. Its location in the text is dictated by its importance in discussing undrained loading and the shear strength of soils.

The theory of consolidation, as well as unsteady-state flow analysis, require the combining of the volume change characteristics of a soil with its permeability characteristics. These analyses have formed an integral part of saturated soil mechanics and greatly assist the engineer in understanding soil behavior. Chapter 15 deals with the one-dimensional theory of consolidation, while Chapter 16 presents two- and three-dimensional, unsteady-state flow for unsaturated soils. The theory related to surface flux boundary conditions, as it relates to microclimatic conditions, is briefly presented in Chapter 16.

There is a great need for case histories to illustrate and substantiate the theories related to unsaturated soil behavior. One of the main objectives of this book is to synthesize the available research information and solidify an unsaturated soil theoretical context in order to form a basis for future studies in the form of case histories.

The book is the result of many years of study, research, and help from numerous persons. We thank the many authors and publishers for permission to reproduce figures and use information from research papers.

We want to acknowledge the support provided for the preparation of the manuscript. We thank Professor P. N. Nikiforuk, Dean of the College of Engineering, University of Saskatchewan, Saskatoon, Canada, and Professor Chen Charng Ning, Dean of the School of Civil and Structural Engineering, Nanyang Technological University, Singapore, for their encouragement and support. Thanks to Mr. A. W. Clifton, Clifton Associates Ltd., Regina, Canada, who was particularly instrumental in ensuring that the theoretical concepts and formulations for unsaturated soils were in a form which could readily be put into engineering practice. Several students and colleagues provided invaluable assistance in the review of the manuscript. Recognition is due to Dr. S. L. Barbour and Dr. G. W. Wilson for their review of several chapters. Miss E. Imre of Budapest, Hungary, provided helpful review of several chapters. Dr. D. E. Pufahl reviewed Chapter 2, and Dr. D. Y. F. Ho reviewed Chapters 9 and 10. We are particularly grateful to Professor N. R. Morgenstern who has continued to provide insight and encouragement into the study of the behavior of unsaturated soils.

We also wish to thank the typists, Mrs. Gladie Russell, Mr. Mark Vanstone, Miss Tracey Regier, Miss Kerri Fischer, and Mrs. Leslie Pavier for their endurance and meticulous typing of our many drafts. We are particularly grateful to Mrs. Pavier who organized the many persons involved in producing the final manuscript. Mr. J. L. Loi took a keen interest in the drafting of the figures, the replotting of figures to SI units, and the checking of data. Miss Kyla Fischer and Ms. Deidre S. Komarychka performed meticulous work in preparing the figures. The authors wish to acknowledge the excellent editing and proofreading of all the chapters by Mr. Sai K. Vanapalli, Mr. Julian Gan and Dr. A. Xing. Mr. L. Lam analyzed several of the example problems in Chapters 7 and 16. Mr. J. Lau and Mr. K. Fredlund organized the extensive list of references for the book. The work and efforts of other graduate students are deeply appreciated.

D. G. Fredlund
H. Rahardjo

University of Saskatchewan
April 1993

CONTENTS

CHAPTER 1 Introduction to Unsaturated Soil Mechanics 1

1.1 Role of Climate 1

1.2 Types of Problems 3

1.2.1 Construction and Operation of a Dam 3

1.2.2 Natural Slopes Subjected to Environmental Changes 5

1.2.3 Mounding Below Waste Retention Ponds 6

1.2.4 Stability of Vertical or Near Vertical Excavations 6

1.2.5 Lateral Earth Pressures 7

1.2.6 Bearing Capacity for Shallow Foundations 7

1.2.7 Ground Movements Involving Expansive Soils 8

1.2.8 Collapsing Soils 9

1.2.9 Summary of Unsaturated Soils Examples 9

1.3 Typical Profiles of Unsaturated Soils 9

1.3.1 Typical Tropical Residual Soil Profile 10

1.3.2 Typical Expansive Soils Profile 11

1.4 Need for Unsaturated Soil Mechanics 12

1.5 Scope of the Book 13

1.6 Phases of an Unsaturated Soil 14

1.6.1 Definition of a Phase 14

1.6.2 Air–Water Interface or Contractile Skin 14

1.7 Terminology and Definitions 15

1.8 Historical Developments 16

CHAPTER 2 Phase Properties and Relations 20

2.1 Properties of the Individual Phases 20

2.1.1 Density and Specific Volume 21

Soil particles 21

Water phase 21

Air phase 21

2.1.2 Viscosity 23

2.1.3 Surface Tension 24

2.2 Interaction of Air and Water 25

2.2.1 Solid, Liquid, and Vapor States of Water 26

2.2.2 Water Vapor 26

2.2.3 Air Dissolving in Water 27

Solubility of Air in Water 28

Diffusion of Gases Through Water 28

2.3 Volume–Mass Relations 29
2.3.1 Porosity 29
2.3.2 Void Ratio 30
2.3.3 Degree of Saturation 30
2.3.4 Water Content 31
2.3.5 Soil Density 32
2.3.6 Basic Volume–Mass Relationship 32
2.3.7 Changes in Volume–Mass Properties 33
2.3.8 Density of Mixtures Subjected to Compression of the Air Phase 34
Piston–porous stone analogy 34
Conservation of mass applied to a mixture 36
Soil particles–water–air mixture 37
Air–water mixture 37

CHAPTER 3 Stress State Variables 38
3.1 History of the Description of the Stress State 38
3.1.1 Effective Stress Concept for a Saturated Soil 38
3.1.2 Proposed Effective Stress Equation for an Unsaturated Soil 39
3.2 Stress State Variables for Unsaturated Soils 42
3.2.1 Equilibrium Analysis for Unsaturated Soils 42
Normal and shear stresses on a soil element 42
Equilibrium equations 43
3.2.2 Stress State Variables 43
Other combinations of stress state variables 44
3.2.3 Saturated Soils as a Special Case of Unsaturated Soils 45
3.2.4 Dry Soils 45
3.3 Limiting Stress State Conditions 46
3.4 Experimental Testing of the Stress State Variables 47
3.4.1 The Concept of Axis Translation 47
3.4.2 Null Tests to Test Stress State Variables 48
3.4.3 Other Experimental Evidence in Support of the Proposed Stress State Variables 48
3.5 Stress Analysis 49
3.5.1 *In Situ* Stress State Component Profiles 49
Coefficient of lateral earth pressure 52
Matric suction profile 53
Ground surface condition 53
Environmental conditions 53
Vegetation 53
Water table 54
Permeability of the soil profile 54
3.5.2 Extended Mohr Diagram 54
Equation of Mohr circles 55
Construction of Mohr circles 56
3.5.3 Stress Invariants 58
3.5.4 Stress Points 59
3.5.5 Stress Paths 59
3.6 Role of Osmotic Suction 63

CHAPTER 4 Measurements of Soil Suction 64
4.1 Theory of Soil Suction 64
4.1.1 Components of Soil Suction 64
4.1.2 Typical Suction Values and Their Measuring Devices 66
4.2 Capillarity 67
4.2.1 Capillary Height 67
4.2.2 Capillary Pressure 68
4.2.3 Height of Capillary Rise and Radius Effects 69
4.3 Measurements of Total Suction 70
4.3.1 Psychrometers 70
Seebeck effects 70
Peltier effects 70
Peltier psychrometer 71
Psychrometer calibration 73
Psychrometer performance 74
4.3.2 Filter paper 77
Principle of measurement (filter paper method) 77
Measurement and calibration techniques (filter paper method) 77
The use of the filter paper method in practice 79
4.4 Measurements of Matric Suction 80
4.4.1 High Air Entry Disks 81
4.4.2 Direct measurements 82
Tensiometers 83
Servicing the tensiometer prior to installation 84
Servicing the tensiometer after installation 86
Jet fill tensiometers 86
Small tip tensiometer 86
Quick Draw tensiometers 88
Tensiometer performance for field measurements 88
Osmotic tensiometers 90
Axis-translation technique 91
4.4.3 Indirect Measurements 93
Thermal conductivity sensors 95
Theory of operation 97
Calibration of sensors 97
Typical results of matric suction measurements 99
The MCS 6000 sensors 99
The AGWA-II sensors 100
4.5 Measurements of Osmotic Suction 104
4.5.1 Squeezing technique 105

CHAPTER 5 Flow Laws 107
5.1 Flow of Water 107
5.1.1 Driving Potential for Water Phase 108
5.1.2 Darcy's Law for Unsaturated Soils 110
5.1.3 Coefficient of Permeability with Respect to the Water Phase 110
Fluid and porous medium components 110

Relationship between permeability and volume-mass properties 111

Effect of variations in degree of saturation on permeability 111

Relationship between coefficient of permeability and degree of saturation 111

Relationship between water coefficient of permeability and matric suction 113

Relationship between water coefficient of permeability and volumetric water content 113

Hysteresis of the permeability function 116

5.2 Flow of Air 117

5.2.1 Driving Potential for Air Phase 117

5.2.2 Fick's Law for Air Phase 117

5.2.3 Coefficient of Permeability with Respect to Air Phase 119

Relationship between air coefficient of permeability and degree of saturation 120

Relationship between air coefficient of permeability and matric suction 120

5.3 Diffusion 121

5.3.1 Air Diffusion Through Water 121

5.3.2 Chemical Diffusion Through Water 123

5.4 Summary of Flow Laws 123

CHAPTER 6 Measurement of Permeability 124

6.1 Measurement of Water Coefficient of Permeability 124

6.1.1 Direct Methods to Measure Water Coefficient of Permeability 124

Laboratory test methods 124

Steady-state method 124

Apparatus for steady-state method 125

Computations using steady-state method 126

Presentation of water coefficients of permeability 126

Difficulties with the steady-state method 127

Instantaneous profile method 127

Instantaneous profile method proposed by Hamilton et al. 128

Computations for the instantaneous profile method 129

In situ field methods 130

In situ instantaneous profile method 130

Computations for the in situ instantaneous profile method 131

6.1.2 Indirect Methods to Compute Water Coefficient of Permeability 133

Tempe pressure cell apparatus and test procedure 133

Volumetric pressure plate extractor apparatus and test procedure 134

Test procedure for the volumetric pressure plate extractor 135

Drying portion of soil-water characteristic curve 136

Wetting portion of the soil–water characteristic curve 136
Computation of k_w using the soil–water characteristic curve 136
6.2 Measurement of Air Coefficient of Permeability 138
Triaxial permeameter cell for the measurement of air permeability 140
Triaxial permeameter cell for air and water permeability measurements 140
6.3 Measurement of Diffusion 143
6.3.1 Mechanism of Air Diffusion Through High Air Entry Disks 144
6.3.2 Measurements of the Coefficient of Diffusion 144
Procedure for computing diffusion properties 145
6.3.3 Diffused Air Volume Indicators 146
Bubble pump to measure diffused air volume 146
Diffused air volume indicator (DAVI) 146
Procedure for measuring diffused air volume 148
Computation of diffused air volume 148
Accuracy of the diffused air volume indicator 149

CHAPTER 7 Steady-State Flow 150
7.1 Steady-State Water Flow 150
7.1.1 Variation of Coefficient of Permeability with Space for an Unsaturated Soil 151
Heterogeneous, isotropic steady-state seepage 151
Heterogeneous, anisotropic steady-state seepage 151
7.1.2 One-Dimensional Flow 152
Formulation for one-dimensional flow 153
Solution for one-dimensional flow 154
Finite difference method 155
Head boundary condition 155
Flux boundary condition 156
7.1.3 Two-Dimensional Flow 159
Formulation for two-dimensional flow 159
Solutions for two-dimensional flow 160
Seepage analysis using the finite element method 161
Examples of two-dimensional problems 164
Infinite slope 171
7.1.4 Three-Dimensional Flow 173
7.2 Steady-State Air Flow 175
7.2.1 One-Dimensional Flow 175
7.2.2 Two-Dimensional Flow 176
7.3 Steady-State Air Diffusion Through Water 177

CHAPTER 8 Pore Pressure Parameters 178
8.1 Compressibility of Pore Fluids 178
8.1.1 Air Compressibility 179
8.1.2 Water Compressibility 179
8.1.3 Compressibility of Air–Water Mixtures 179
The use of pore pressure parameters in the compressibility equation 181

8.1.4 Components of Compressibility of an Air–Water Mixture 181
Effects of free air on the compressibility of the mixture 182
Effects of dissolved air on the compressibility of the mixture 182
8.1.5 Other Relations for Compressibility of Air–Water Mixture 182
Limitation of Kelvin's equation in formulating the compressibility equation 183
8.2 Derivations of Pore Pressure Parameters 184
8.2.1 Tangent and Secant Pore Pressure Parameters 185
8.2.2 Summary of Necessary Constitutive Relations 186
8.2.3 Drained and Undrained Loading 188
8.2.4 Total Stress and Soil Anisotropy 190
8.2.5 K_0-Loading 191
8.2.6 Hilf's Analysis 192
8.2.7 Isotropic Loading 194
8.2.8 Uniaxial Loading 196
8.2.9 Triaxial Loading 196
8.2.10 Three-Dimensional Loading 199
8.2.11 α Parameters 200
8.3 Solutions of the Pore Pressure Equations and Comparisons with Experimental Results 201
8.3.1 Secant B_h' Pore Pressure Parameter Derived from Hilf's Analysis 201
8.3.2 Graphical Procedure for Hilf's Analysis 202
8.3.3 Experimental Results of Tangent B Pore Pressure Parameters for Isotropic Loading 204
8.3.4 Theoretical Prediction of B Pore Pressure Parameters for Isotropic Loading 206
8.3.5 Experimental Results of Tangent B and A Parameters for Triaxial Loading 215
8.3.6 Experimental Measurements of the α Parameter 216

CHAPTER 9 Shear Strength Theory 217
9.1 History of Shear Strength 217
9.1.1 Data Associated with Incomplete Stress Variable Measurements 224
9.2 Failure Envelope for Unsaturated Soils 225
9.2.1 Failure Criteria 225
9.2.2 Shear Strength Equation 227
9.2.3 Extended Mohr–Coulomb Failure Envelope 228
9.2.4 Use of $(\sigma - u_w)$ and $(u_a - u_w)$ to Define Shear Strength 230
9.2.5 Mohr–Coulomb and Stress Point Envelopes 231
9.3 Triaxial Tests on Unsaturated Soils 236
9.3.1 Consolidated Drained Test 238
9.3.2 Constant Water Content Test 238
9.3.3 Consolidated Undrained Test with Pore Pressure Measurements 240
9.3.4 Undrained Test 243
9.3.5 Unconfined Compression Test 245

9.4 Direct Shear Tests on Unsatured Soils 247
9.5 Selection of Strain Rate 248
9.5.1 Background on Strain Rates for Triaxial Testing 248
9.5.2 Strain Rates for Triaxial Tests 250
9.5.3 Displacement Rate for Direct Shear Tests 254
9.6 Multistage Testing 255
9.7 Nonlinearity of Failure Envelope 255
9.8 Relationships Between ϕ^b and χ 258

CHAPTER 10 Measurement of Shear Strength Parameters 260
10.1 Special Design Considerations 260
10.1.1 Axis-Translation Technique 260
10.1.2 Pore–Water Pressure Control or Measurement 263
Saturation procedure for a high air entry disk 266
10.1.3 Pressure Response Below the Ceramic Disk 266
10.1.4 Pore–Air Pressure Control or Measurement 272
10.1.5 Water Volume Change Measurement 273
10.1.6 Air Volume Change Measurement 275
10.1.7 Overall Volume Change Measurement 275
10.1.8 Specimen Preparation 276
10.1.9 Backpressuring to Produce Saturation 277
10.2 Test Procedures for Triaxial Tests 279
10.2.1 Consolidated Drained Test 280
10.2.2 Constant Water Content Test 281
10.2.3 Consolidated Undrained Test with Pore Pressure Measurements 281
10.2.4 Undrained Test 282
10.2.5 Unconfined Compression Test 282
10.3 Test Procedures for Direct Shear Tests 282
10.4 Typical Test Results 284
10.4.1 Triaxial Test Results 284
Consolidated drained triaxial tests 284
Constant water content triaxial tests 286
Nonlinear shear strength versus matric suction 286
Undrained and unconfined compression tests 288
10.4.2 Direct Shear Test Results 289

CHAPTER 11 Plastic and Limit Equilibrium 297
11.1 Earth Pressures 297
11.1.1 At Rest Earth Pressure Conditions 298
11.1.2 Estimation of Depth of Cracking 300
11.1.3 Extended Rankine Theory of Earth Pressures 301
Active earth pressure 303
Coefficient of active earth pressure 304
Active earth pressure distribution (constant matric suction with depth) 304
Tension zone depth 304
Active earth pressure distribution (linear decrease in matric suction to the water table) 304

Active earth pressure distribution when the soil has tension cracks 305
Passive earth pressure 307
Coefficient of passive earth pressure 307
Passive earth pressure distribution (constant matric suction with depth) 307
Passive earth pressure distribution (linear decrease in matric suction to the water table) 308
Deformations with active and passive states 308
11.1.4 Total Lateral Earth Force 309
Active earth force 310
Passive earth force 311
11.1.5 Effect of Changes in Matric Suction on the Active and Passive Earth Pressure 312
Relationship between swelling pressures and the earth pressures 313
11.1.6 Unsupported Excavations 313
Effect of tension cracks on the unsupported height 314
11.2 Bearing Capacity 315
11.2.1 Terzaghi Bearing Capacity Theory 315
11.2.2 Assessment of Shear Strength Parameters and a Design Matric Suction 317
Stress state variable approach 317
Total stress approach 318
11.2.3 Bearing Capacity of Layered Systems 319
11.3 Slope Stability 320
11.3.1 Location of the Critical Slip Surface 320
11.3.2 General Limit Equilibrium (GLE) Method 321
Shear force mobilized equation 323
Normal force equation 324
Factor of safety with respect to moment equilibrium 324
Factor of safety with respect to force equilibrium 325
Interslice force function 325
Procedures for solving the factors of safety equation 327
Pore-water pressure designation 328
11.3.3 Other Limit Equilibrium Methods 330
11.3.4 Numerical Difficulties Associated with the Limit Equilibrium Method of Slices 332
11.3.5 Effects of Negative Pore-Water Pressure on Slope Stability 333
The "total cohesion" method 333
Two examples using the "total cohesion" method 334
Example no. 1 334
Example no. 2 338
The "extended shear strength" method 340
General layout of problems and soil properties 340
Initial conditions for the seepage analysis 342
Seepage and slope stability results under high-intensity rainfall conditions 344

CHAPTER 12 Volume Change Theory 346

12.1 Literature Review 346

12.2 Concepts of Volume Change and Deformation 349

12.2.1 Continuity Requirements 349

12.2.2 Overall Volume Change 350

12.2.3 Water and Air Volume Changes 351

12.3 Constitutive Relations 351

12.3.1 Elasticity Form 351

Water phase constitutive relation 353

Change in the volume of air 353

Isotropic loading 354

Uniaxial loading 354

Triaxial loading 354

K_0*-loading* 356

Plane strain loading 357

Plane stress loading 357

12.3.2 Compressibility Form 357

12.3.3 Volume–Mass Form (Soil Mechanics Terminology) 358

12.3.4 Use of $(\sigma - u_w)$ and $(u_a - u_w)$ to Formulate Constitutive Relations 358

12.4 Experimental Verifications for Uniqueness of Constitutive Surfaces 360

12.4.1 Sign Convention for Volumetric Deformation Properties 361

12.4.2 Verification of Uniqueness of the Constitutive Surfaces Using Small Stress Changes 361

12.4.3 Verification of the Constitutive Surfaces Using Large Stress State Variable Changes 363

12.5 Relationship Among Volumetric Deformation Coefficients 365

12.5.1 Relationship of Volumetric Deformation Coefficients for the Void Ratio and Water Content Surfaces 366

12.5.2 Relationship of Volumetric Deformation Coefficients for the Volume–Mass Form of the Constitutive Surfaces 367

12.5.3 Laboratory Tests Used for Obtaining Volumetric Deformation Coefficients 367

12.5.4 Relationship of Volumetric Deformation Coefficients for Unloading Surfaces 369

12.5.5 Relationship of Volumetric Deformation Coefficients for Loading and Unloading Surfaces 370

12.5.6 Constitutive Surfaces on a Semi-Logarithmic Plot 370

CHAPTER 13 Measurements of Volume Change Indices 374

13.1 Literature Review 374

13.2 Test Procedures and Equipments 376

13.2.1 Loading Constitutive Surfaces 377

Oedometer tests 378

Pressure plate drying tests 379

Shrinkage tests 380